... frequency response ... response). Modulation of the FDF provides a solution.

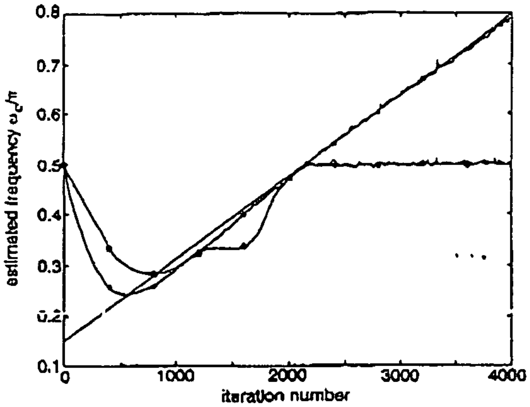

Fig. 2 *Comparison of MLAFE and ULAFE tracking chirp*

—— chirp frequency
O ULAFE
* MLAFE

Conclusions: An improvement to the AFE algorithm is presented which allows for more accurate frequency estimates at a slightly higher computational cost. Additionally, the proposed MLAFE algorithm is able to track time-varying frequencies, which the AFE cannot.

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References

1 HAYKIN S., and LITVA J. *in* SHEPHERD T.J. (Ed.): 'Radar array processing' (Springer-Verlag, 1993)
2 ETTER, D.M., and HUSH, D.R.: 'A new technique for adaptive frequency estimation and tracking', *IEEE Trans.*, 1987, ASSP-35, (4), pp. 561–564
3 CAIN, G.D., MURPHY, N.P., and TARCZYNSKI, A.: 'Evaluation of several variable FIR fractional-sample delay filters'. ICASSP Proc., 1994, pp. 621–624
4 LAAKSO, T.I., VÄLIMÄKI, V., KARJALAINEN, M., and LAINE, U.K.: 'Splitting the unit delay', *Signal Process. Mag.*, 1996, 13, (1), pp. 30–60
5 HERMANOWICZ, E.: 'Explicit formulas for weighting coefficients of maximally flat tunable FIR delayers', *Electron. Lett.*, 1992, 28, (20), pp. 1936–1937
6 DOOLEY, S.R., and NANDI, A.K.: 'Adaptive subsample time delay estimation using Lagrange interpolators', submitted to *IEEE Sig. Proc. Lett.*, 1998

High-speed DQPSK chirp spread spectrum system for indoor wireless applications

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A chirp spread spectrum communication link for high-speed indoor wireless systems using a broadband SAW chirp filter is proposed. This system combines the multipath resolving ability of spread spectrum with the diversity of a RAKE-type receiver. Computer simulations and experimental results show nearly ideal performance in multipath fading conditions.

Introduction: Pulse compression of linear swept signals (chirps) is a well-known technique and has been proposed for use in spread spectrum systems [1] for many years. Unfortunately, so-called chirp spread spectrum systems have not been widely implemented because direct sequence (DS-SS) was considered more bandwidth efficient and easier to implement. At the high carrier frequencies and data rates proposed for indoor wireless systems, however, chirp spread spectrum's ability to overcome frequency selective fading with a simple surface acoustic wave (SAW) implementation makes it more suitable.

System description: In our prototype system shown in Fig. 1, a dispersive SAW device is used to spread a relatively high bit rate (10Mbit/s) DQPSK signal. The modulated DQPSK data is passed through an RF switch to provide a broadband probing pulse. The chirps produced by the SAW are then upconverted to 1.8GHz (in future tests this will be increased to 17GHz) and sent over the wireless channel.

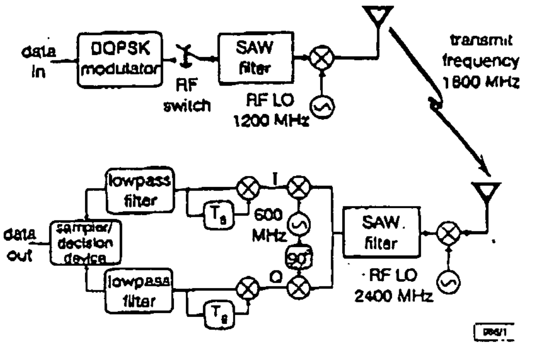

Fig. 1 *Simplified block diagram of prototype chip spread spectrum system*

At the receiver, the transmitted signal is sideband inverted and correlated through the receive SAW filter. The inversion process converts the transmitted up-chirp to a down-chirp and allows identical filters to be used in both the transmitter and receiver, resulting in better phase matching. After correlation, the I and Q components are extracted and the phase removed in anticipation of DQPSK demodulation. At this point a lowpass filter with a cutoff frequency of $1/T_s$ (where T_s is the symbol time) is implemented as a simple but efficient RAKE to sum the energy of the multipath components. After the RAKE a decision device recovers the original data symbols.

It is the three main system components (the chirp correlator, the DQPSK demodulator and the RAKE structure) acting in concert which give the system its excellent performance in the presence of frequency selective fading.

SAW design and testing: A SAW device was fabricated specifically for this project on Y-Z $LiNbO_3$ using a very simple slanted array compressor (SAC) design. Manufacturing constraints limited the centre frequency to 600MHz and the bandwidth to 200MHz. The length of the chirp pulse produced by the SAW is ~500ns giving a time-bandwidth product of 100. The SAW device has a measured passband insertion loss of ~32dB with no impedance matching.

The normalised magnitude response of the SAW correlation pulse is shown in Fig. 2. Unwanted effects, such as triple transit and electromagnetic feedthrough reduced the maximum peak-to-sidelobe ratio to ~34dB, while the transmit/receive filter phase errors widened the correlation pulse to ~25ns. The measured system processing gain is ~16dB.

Test and simulation results: Computer simulated BER curves using measured indoor radio channels and a data rate of 10Mbit/s are shown in Fig. 3. The curves represent both an ideal system using a mathematical chirp (i.e. the transmit and receive filters modelled by a linear chirp function with Hamming windowing), and a more practical system using the measured frequency response of our SAW device. As a reference, the BER curve for DQPSK in a Gaussian channel is shown (taken from equations in [4]). These curves show a performance within ~2dB of theoretical DQPSK.

The ... ...ate that ... when a practical sub-optimal SAW device is substituted for a perfect chirp (~1 dB).

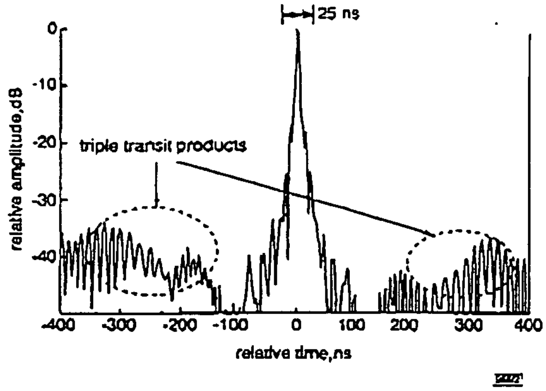

Fig. 2 *Correlation pulse produced by transmitter and receiver SAW filters*

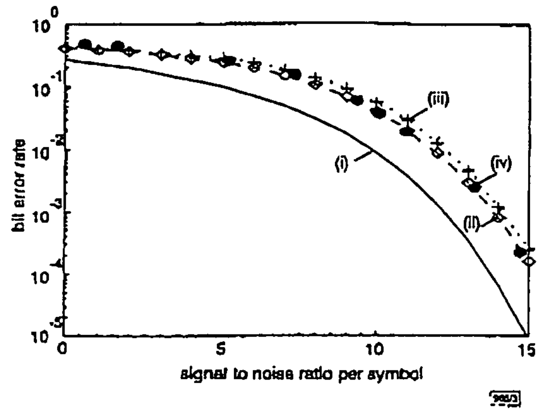

Fig. 3 *BER curves for DQPSK (Gaussian channel), mathematical chirp simulation, measured SAW filter simulation and measured prototype hardware (10m NLOS cannel)*

(i) DQPSK
(ii) Chirp simulation
(iii) SAW filter simulation
(iv) Measured prototype hardware

The channel impulse responses used in the simulations were taken at random from an extensive indoor channel database [3] with over 10000 individual measurements. The channels were measured from 700 to 1100 MHz at many different office locations and receive-transmit distances. For our simulations, we used only channels with a receiver-transmitter distance of 10m, giving an average $\tau_{RMS} \simeq 20.7$ns. When ISI is not a factor (i.e. symbol times were greater than 8–10 times τ_{RMS}) error rates of $< 10^{-7}$ were readily achievable without coding.

Fig. 3 also shows BER measurements for our prototype system (at a data rate of 10 Mbit/s) using a transmit-receive distance of 10m, a carrier frequency of 1800 MHz and a non-line-of-sight channel. This channel had an average measured excess delay of ~250 ns. The measured points fall very close to both simulated curves, thus verifying the computer results.

In measurements with similar 10m channels we were regularly able to produce BERs of $< 10^{-5}$ with symbol times as low as 100 ns (i.e. data rates of 20 Mbit/s).

Conclusions: In this Letter, we have shown the viability of a simple SAW-based chirp spread spectrum communications scheme for the indoor wireless environment. The multipath resolving capability of the SAW correlator, in conjunction with the RAKE implementation permitted by using DQPSK, provides immunity to frequency selective fading. Simulations and hardware testing show that excellent performance is achievable even using a sub-optimal SAW device. Results indicate that raw throughputs in excess of 20 Mbit/s are possible at error rates of $< 10^{-5}$.

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References

1 GOTT, G.F., and KARIA, A.J.: 'Differential phase-shift keying applied to chirp data signals', *Proc. IEE*, 1974, 121, (9), pp. 923–928
2 CAMPBELL, C.: 'Surface acoustic wave devices and their signal processing applications' (Academic Press, Boston, 1989)
3 THOLL, D.: 'Characterization of the UHF indoor radio propogation channel', MSc Thesis, University of Calgary, 1995
4 PROAKIS, J.G.: 'Digital communications' (McGraw-Hill, New York, 1995)

Interference in DS-CDMA systems with exponentially vanishing autocorrelations: Chaos-based spreading is optimal

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A novel estimation of the minimum achievable interference in direct sequence-code division multiple access (DS-CDMA) systems is introduced, which holds when spreading sequences with exponentially vanishing autocorrelation are employed. This can be applied to many of the recently proposed improvements to classical maximum-length or Gold sequences, such as chaos-based spreading. Asymptotic, infinite-bandwidth results are also provided, clarifying the maximum attainable gain. Empirical evidence shows that this theoretical maximum is achieved by some chaos-based sequences which are therefore optimal.

Introduction: The classical approach to direct sequence-code division multiple access (DS-CDMA) system design aims to obtain spreading sequences with rapidly vanishing, possibly delta-like autocorrelation functions. Though this may positively affect some sequence acquisition mechanisms, it does not necessarily minimise co-channel interference in an asynchronous environment. In fact, following a well established path [1], the interference seen by U users due to the presence of other competing users can be thought of as a zero-mean Gaussian random variable, the variance of which, normalised to the useful signal power (σ^2), gives a bit error probability $P_{err} = \mathrm{erfc}\sqrt{[1/(2\sigma^2)]}$.

More formally, we consider a spreading factor N which is also the period of (possibly) complex spreading sequences $y = y_0, y_1, \ldots, y_{N-1}, y_0, y_1, \ldots$ where y_i is one of the Lth complex roots of 1. With this, $\sigma^2 = (U-1)\,R/2$ and [2]

$$R = \frac{1}{3N^2}\sum_{\tau=1-N}^{N-1}\left\{2E[|\Gamma_{N,\tau}|^2] + \mathrm{Re}(E[\Gamma_{N,\tau}\Gamma^*_{N,\tau+1}])\right\}$$

where the expectation E is taken over all the pairs of sequences y', y'' that can be assigned to two users and $\Gamma_{N,\tau} = \sum_{k=0}^{N-\tau-1} y'_k (y''_{k+\tau})^*$ for $\tau = 0, 1, \ldots, N-1$, $\Gamma_{N,\tau} = \sum_{k=0}^{N+\tau-1} y'_{k-\tau}(y''_k)^*$ for $\tau = -1, -2, \ldots, -N+1$ and $\Gamma_{N,\tau} = 0$ for $|\tau| \geq N$ ($\cdot^*$ denoting the complex conjugate).

The quantity R assumes the significance of *expected interference-to-signal ratio per interfering user* and must be minimised to improve communication quality. To investigate this issue we define $A_l = E[y_l y_0^*]$ and assume that second-order stationarity holds so that $E[y_{j+l} y_j^*] = A_l$ for any $l > 0$ (note that $A_0 = 1$). With this, algebraic manipulation leads to

$$R = \frac{2}{3N} + \frac{4}{3N^3}\sum_{l=1}^{N-1}\left[(N-l)^2|A_l|^2 + \binom{N-l+1}{2}\mathrm{Re}(A_{l-1}A_l^*)\right] \qquad (1)$$